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The use of Helmholtz resonator type transducers for low-frequency, high-power deep-ocean applications is discussed. The frequency range of interest is 200 Hz and above at radiated acoustic power levels up to 2 kW. Analysis and design tradeoffs are discussed.

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Contents

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UNDERWATER HELMHOLTZ RESONATOR TRANSDUCERS FOR LOW-FREQUENCY, HIGH POWER APPLICATIONS

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I. UNDERWATER HELMHOLTZ RESONATORS

When considering low-frequency underwater acoustic sources, it is recognized that, in general, the radiating device will be small when compared to the acoustic wavelength in the medium. It is this condition, not poor design practices, which precipitates the large size and weight, low efficiency, and relatively poor reliability from which high power, low-frequency sources suffer. The diminishing real part of the radiation impedance dictates ı w efficiency and large required volume velocities; large volume velocitie , in turn infer large force, and therefore, heavy and robust devices. When these inherent difficulties are coupled with the requirement of operation at deep ocean depths, the problems facing the transducer designer become greatly magnified. Several transduction mechanisms, in different design configurations, are capable of producing high source levels over low-frequency bandwidths of an octave or more. Most of these designs, however, require some form of depth compensation and/or pressure release for the interior of the radiator which either limits the operational depth capability of the device or greatly increases its complexity. Aside from the obvious constraints of output power and bandwidth, the design of low-frequency transducers is determined by the trade-off between achieving the operational depth capability and the restraints on size and weight. The ideal device is one which meets all of the electro-acoustic requirements while operating independently of water depth. The search for the ideal solution naturally leads to the consideration of design configurations which can be "free-flooded"; that is, configurations where no pressure differential exists across any portion of the transducer due to the surrounding hydrostatic pressure.

The Helmholtz resonator basically consists of a closed rigid cavity coupled to the external medium through an opening or orifice, as depicted in Figure 1, and as such is a "free-flooded" device. Helmholtz resonators have been used as filter elements in air acoustics and as narrow bandwidth sources in underwater acoustics. The application under consideration here, however, is the use of a Helmholtz resonator to increase the low-frequency output of a piezoelectric ceramic radiator as shown in Fig. 2. As shown in the figure, well below the frequency of its first resonance, a piezoelectric radiator normally has a positive 12-dB-per-octave slope in the output sound pressure level per volt as a function of increasing frequency. If, however, the ceramic element is used in a configuration where one of its surfaces radiates directly into the unbounded medium and the other surface radiates into the fluid-filled cavity of a Helmholtz resonator, there will be a resultant increase in the output sound pressure level at the Helmholtz resonance frequency. In this type of transducer, the ceramic radiator could generally be in the form of one of three basic configurations in which all or part of the Helmholtz cavity is formed by the ceramic. These three configurations are shown in Fig. 3. The most simple configuration is that of a piezoelectric ceramic sphere where the interior volume of the sphere forms the Helmholtz cavity.[1] This design, however, would not generally be considered feasible for the frequencies desired because the mosaic construction required for large sizes makes the sphere relatively fragile and expensive. In the second configuration, a piezoelectric ceramic tube forms all but the ends of a cylindrical cavity.[2] The large sizes required by low-frequency applications dictate that the ceramic tube be fabricated from a stack of segmented ceramic rings as shown in the figure. In this configuration, to assure that the ceramic remains in compression, the rings must be radially prestressed by wrapping them with a glass-fiber/epoxy composite. The ring segments may be either radially or circumferentially poled although poling thickness limitations generally make circumferential poling preferable. The third configuration consists of a cylindrical metal housing with a ceramic flexural disc at one end. The flexural disc may be either bilaminar or trilaminar in construction; that is, with a mosaic of piezoelectric ceramic laminated to either one or both sides of a metal disc. Of the two configurations considered feasible for low-frequency applications, each has advantages over the other dependent primarily upon geometry constraints. When the requirements do not constrain the diameter, the flexural disc would be the most efficient radiator; if the diameter is constrained, however, the segmented ceramic rings would become the preferred radiator.

II. DESIGN CRITERIA

From the simple equation for the resonance frequency of a Helmholtz resonator

$$f_r = \frac{1}{2\pi}\sqrt{\frac{1}{C_c M_A}} , \tag{1}$$

where C_c is the compliance of the cavity and M_A is the inertance of the orifice; it would appear to be possible to design a device for operation at low frequencies with a small orifice radius and small cavity volume. However, internal losses increase with decreasing orifice size and cavity volume. Decreasing the cavity volume also decreases the volume of ceramic in the transducer and, therefore, the maximum available volume velocity. In other words, the orifice size and cavity volume may be decreased only at the expense of a lower acoustic output power capability. Obviously then, for high-power applications, it is desirable to maximize the orifice size and cavity volume within the size and weight restraints of the requirements.

In reality, the Helmholtz resonance frequency for a given orifice inertance is determined not only the compliance of the cavity, but by the compliance of the total system. That is, the resonance frequency is influenced by other mechanical compliances in the system such as the compliance of the piezoelectric ceramic driver, C_d. Woollett[3] identified the relationship between the cavity compliance, C_c, and the driver compliance, C_d, as an important design parameter and defined it as

$$\alpha = \frac{C_d}{C_d + C_c} . \tag{2}$$

It can be shown that for a given design, the output power is proportional to the factor $(1 - \alpha)^2$ while the viscous loss in the cavity is inversely proportional to $(1 - \alpha)$. Therefore, if the compliance of the driver becomes large in relation to the compliance of the cavity, the output power will decrease and the viscous loss in the cavity will increase.

The radiated power at the Helmholtz resonance frequency is, of course, determined in large part by the Q of the device. There is maximum, or lossless, Q associated with any Helmholtz resonator and it is primarily dependent upon the size of the transducer. That is, in general, for a given frequency, the larger the transducer becomes, the higher will be its Q, or sharpness of resonance. The Q actually obtained in practice, however, is strongly dependent upon internal losses in the system, primarily viscous losses in the cavity and orifice.

A second parameter which affects the maximum radiated power at the Helmholtz resonance frequency is the fracture stress of the piezoelectric ceramic. If the Q of the system is high, the pressure inside the cavity can cause the fracture stress of the ceramic to be exceeded at high drive levels. The result would be a catastrophic failure of the material. The maximum allowable sound pressure level that can be obtained near the resonance frequency may be determined from the geometry of, and the material used to construct, the ceramic driver.

III. ANALYSIS, MODELING, AND EXPERIMENTAL RESULTS

The most simple model used to describe underwater Helmholtz resonator transducers is a lumped element equivalent circuit. The values for the elements are determined from the geometry of the device and the parameters of the materials used. With all of the mechanical and acoustical elements converted to their electrical equivalents, the model is analyzed through the use of electronic circuit analysis techniques. This traditional modeling approach works quite well as long as the initial assumption of representing the device as a combination of lumped masses, compliances and resistances holds true. For most transducers, this is usually the case when the largest dimension of the radiator is small when compared to the acoustic wavelength in water. When using this technique for Helmholtz resonator transducers, however, additional care must be taken because of the nonlinear losses associated with viscous flow in the cavity and orifice and because, in order to obtain lumped representations of the cavity compliance and orifice inertance, the boundary between the two must be clearly definable. ~~That is,~~ the "aspect ratio", or the ratio of the ORIFICE ~~cavity~~ diameter to THE LENGTH ~~that~~ of the CAVITY ~~orifice~~, becomes an important consideration. As the diameter of the orifice approaches that of the cavity (aspect ratio → 1), the effective inertance and compliance are much more difficult to define and not properly represented as lumped elements; the other extreme, aspect ratio → ∞, is of no interest as a high power radiator. In any case, the electro-mechano-acoustical circuit is a good diagramatic representation in that it clearly shows the two radiators in the system coupled by the compliance of the cavity.

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A further complication in the design of underwater Helmholtz resonators is the structure required to support the active element(s) and to form the cavity closures. Not only must resonances in these structures be avoided for the frequency band of interest, but they must also maintain the stiffness of the cavity. That is, if these structural elements are not stiff enough, they will add to the compliance of the cavity, and therefore, cause a shift in the Helmholtz resonance frequency. A second effect caused by these elements not being "stiff enough" is acoustic radiation from their surfaces exposed to the unbounded medium; that is, one surface of these structures is often exposed to the high pressure in the cavity and the resulting vibration makes them potential radiators. The significance of these structures as radiators is obviously dependent upon their relative amplitudes and phases.

Although this type of structural vibration problem does not lend itself to solution via equivalent circuit analysis, it is ideally suited to the methods of finite element analysis. A relatively new modeling technique we are applying to transducer analysis is: a surface velocity distribution for a transducer structure is generated by a finite element model which is in turn, used as the input to a generalized acoustic radiation impedance model[4]. Experimental feedback is provided via the techniques of modal analysis and, of course, by the measured electroacoustic parameters. Initial results look quite promising.

There is not sufficient space available here to show experimental results, but the oral presentation will compare predicted performance from equivalent circuit and finite element/radiation impedance analyses with measured results for at least three separate devices.

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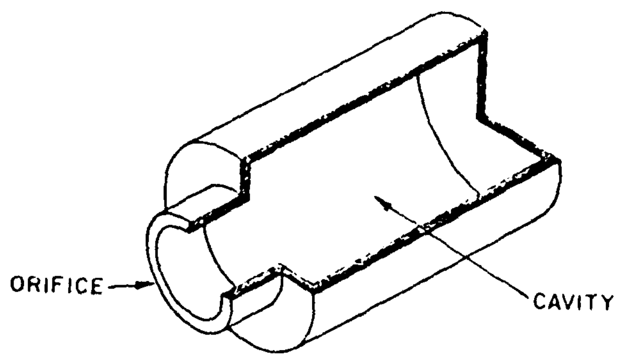

Figure 1. Basic configuration of the Helmholtz Resonator.

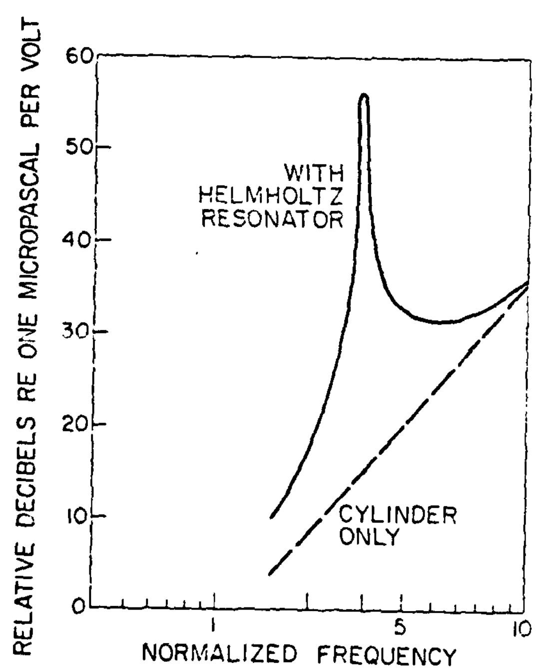

Figure 2. Transmitting voltage response of a fluid-filled piezoelectric ceramic tube with and without a Helmholtz resonator (orifice in one end).

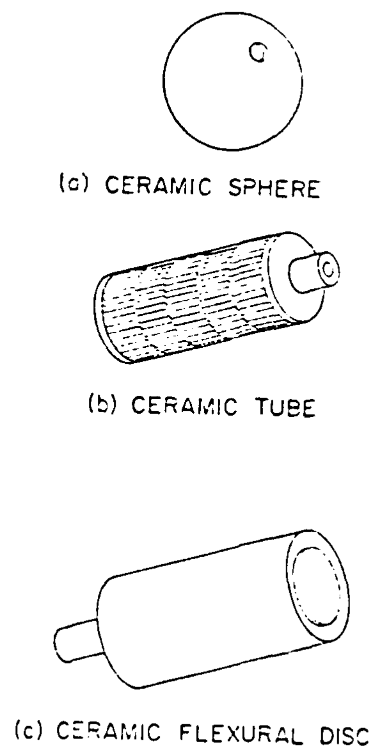

Figure 3. Three basic configurations of underwater piezoelectric Helmholtz resonators.